Final Technical Report

Analysis of Southern California Seismicity Using: (1) Swarms as Transient Detectors, (2) Coda waves for Q Structure and Source Properties

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ABSTRACT

We are analyzing earthquakes recorded by seismic networks in southern California to build on recent improvements in earthquake locations and source characterization. Our work focuses on charactering swarms and foreshock sequences and on systematically estimating earthquake source properties, such as stress drop and radiated energy, using P-wave spectra, and on modeling the scattering and attenuation structure of the southern California crust using coda waves. Building on the catalog of over 60,000 stress-drop estimates that we published over a decade ago, our P-wave spectra analyses now include improved uncertainty estimates that take into account the limited data bandwidth. We are using these results to test issues of earthquake scaling and our previous discovery that swarms and foreshock sequences in southern California tend to have lower-than-average stress drops. In addition, we are characterizing and modeling the P- and S-wave coda (scattering envelope) of earthquakes in southern California to resolve the scattering and attenuation structure of the crust using a Monte Carlo seismic phonon modeling method based on radiative transfer theory. In the long run, our results will provide basic knowledge about earthquake behavior and crustal properties that will increase the ability of seismologists to make realistic forecasts regarding strong motion probabilities in different locations, thus contributing to the goal of reducing losses from earthquakes in the United States.

Results

Swarms

Understanding earthquake clustering in space and time is important but also challenging because of complexities in earthquake patterns and the large and diverse nature of earthquake catalogs. Swarms are of particular interest because they likely result from physical changes in the crust, such as slow slip or fluid flow. Both swarms and clusters resulting from aftershock sequences can span a wide range of spatial and temporal scales. We have developed and implemented a new method to identify seismicity clusters of varying sizes and discriminate them from randomly occurring background seismicity. Our method searches for the closest neighboring earthquakes in space and time and compares the number of neighbors to the background events in larger space/time windows. Applying our method to California's San Jacinto Fault Zone (SJFZ), we found a total of 89 swarm-like groups (Zhang and Shearer, 2016). These groups range in size from 0.14 to 7.23 km and last from 15 minutes to 22 days. The most striking spatial pattern is the larger fraction of swarms at the northern and southern ends of the SJFZ than its central segment, which may be related to more normal-faulting events at the two ends. In order to explore possible driving mechanisms, we studied the spatial migration of events in swarms containing at least 20 events by fitting with both linear and diffusion migration models. Our results suggest that SJFZ swarms are better explained by fluid flow because their estimated linear migration velocities are far smaller than those of typical creep events while large values of best-fitting hydraulic diffusivity are found.

Earthquake source properties from P-wave spectra

Small earthquakes form the overwhelming majority of local earthquake records, but only their locations and magnitudes are routinely cataloged. To understand earthquake physics, scaling relations, and the evolving stress state within southern California, we need to go beyond this. Earthquake stress drop, proportional to the slip divided by the length scale of rupture, is a basic property of earthquakes and is fundamental to the physics of the source and its energy budget (e.g. Kanamori and Brodsky, 2004). Knowledge of the true variability of stress drop is also important for strong ground motion modeling and prediction (e.g., Cotton et al., 2013). Stress drop is commonly estimated by measuring the corner frequency of the seismic source spectrum and assuming a simplified theoretical model of rupture (e.g. Brune, 1970; Madariaga, 1976; Kaneko and Shearer, 2014, 2015). The large number of stress drop studies attest to their importance, but their widely varying results (~0.1 to 100 MPa), the large uncertainties (when calculated), and the ongoing controversy of whether stress drop changes with earthquake magnitude are evidence for how hard it is to calculate reliably (e.g., Abercrombie, 1995, 2013; Abercrombie and Rice, 2005; Shearer et al., 2006; Malagnini et al., 2013; Kwiatek et al., 2014, Abercrombie et al., 2017, and references therein). This uncertainty limits the use of stress drop studies in understanding spatial variations in stress state (e.g., Hauksson, 2014), and predicting strong ground motion (e.g., Baltay et al., 2013, 2017; Baltay and Hanks, 2014).

The main problem in calculating earthquake stress drop is how to separate source and path effects in band-limited signals and so measure corner frequency reliably. Various forms of empirical Green's function (EGF) analysis, in which the seismogram of a co-located small earthquake is used to represent the path effects in a larger earthquake recording, should decrease the trade-offs inherent in extracting the source spectrum (e.g., Kwiatek et al., 2014). If multiple earthquakes, recorded at multiple stations, are combined then it is possible to invert for both source parameters (constant for each event) and path effects (constant for individual paths) using a spectral decomposition approach (e.g., Shearer et al., 2006; Oth et al., 2011).

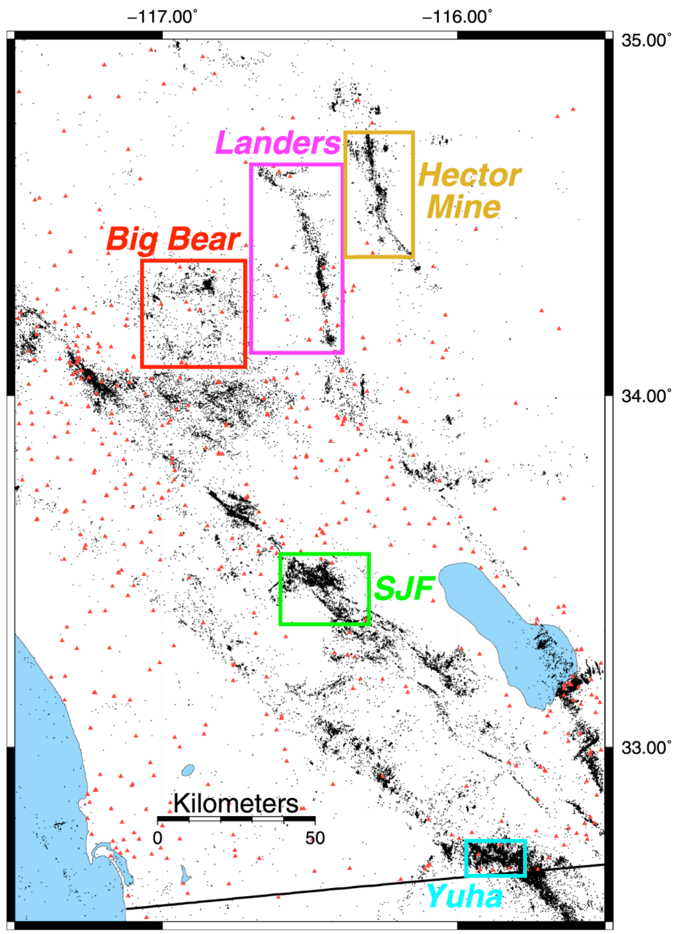

Figure 1. Boundaries of five study regions analyzed in the stress drop study of Trugman and Shearer (2017). Seismicity (black dots) is derived from the relocated catalog of Hauksson et al. (2012), with only *ML* ≥ 1.1 events occurring from Jan. 2002 through Sept. 2016 shown (consistent with the magnitude range and time period of the study). Vertical-component stations from the Southern California Seismic Network are marked as red triangles.

In 2006, we applied spectral decomposition to analyze over 60,000 earthquakes in southern California. Applying an iterative stacking approach to P-wave spectra, we were able to isolate source-, receiver-, and path-dependent terms. Estimated Brune-type stress drops ranged from 0.2 to 20 MPa with no dependence on moment. Despite the large scatter in observed stress drop, spatially coherent variations in median stress drop were apparent, including low values for the Imperial Valley and Northridge aftershocks and higher values for the eastern Transverse ranges. These results are intriguing and still represent the largest stress-drop study ever performed. However, the study suffered from the following limitations: (1) We analyzed data only between 1989 and 2001, a relatively stable period for the SCSN network, but which excluded more recent upgrades to broadband stations and the many additional earthquakes occurring in the last 15 years. (2) Although our approach applied a version of the EGF correction, it did so by simultaneously fitting a large number of stacked source spectra to a single self-similar source model, an approach that may bias the results toward self-similarity (i.e., no scaling of stress drop with moment). (3) The 20 Hz upper bandwidth limit is generally below the corner frequencies of the small events (by far the most numerous in the data set), meaning that their corner frequency estimates are highly uncertain because they rely on the extrapolation of small spectral differences. (4) No error bars or formal uncertainties were included with the stress drop estimates.

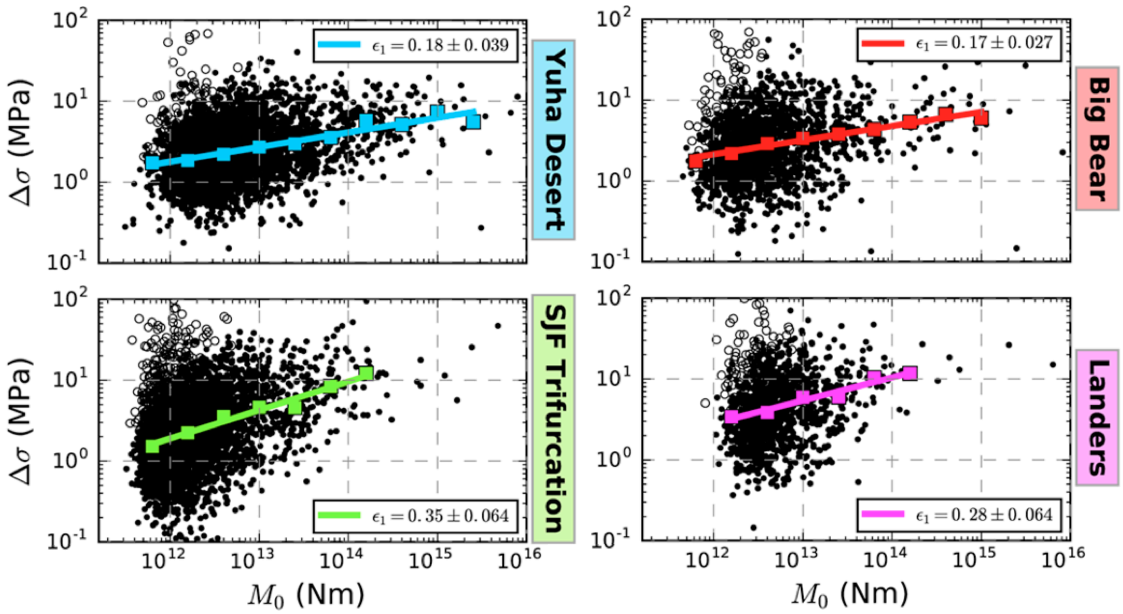

Figure 2. Scaling of estimated stress drop ($\Delta\sigma$) with seismic moment for four of the five study regions in southern California (see Fig. 1). In each panel, the black dots correspond to measurements of source properties for individual events, and the median *fc* and $\Delta\sigma$ in M_0 bins of 0.4 ($\log_{10}$ Nm units) are marked with square symbols. The best-fitting scaling parameter ϵ_1 and two sigma uncertainty for the binned data (obtained from weighted regression analysis) is denoted in each inset and plotted with a solid line. Events with poorly resolved corner frequencies due to bandwidth limitations are marked with open circles.

We have now improved upon the Shearer et al. (2006) method in a number of respects. We use the multi-taper algorithm (Prieto et al., 2009), which provides smoother and more accurate spectra than the Hanning taper used in the 2006 study. We have increased the upper frequency limit to 25 Hz to better capture the corner frequency of smaller events and now apply an automatic algorithm to detect and discard clipped waveforms that can bias the spectral estimates. We apply a bootstrap resampling approach to assess uncertainties in the corner frequency and relative moment estimates. We find that the dominant source of uncertainty comes from the varying spectra from different stations recording the same event, especially in cases where the event is observed by a small number of stations or has poor azimuthal station coverage. Another important result is that the uncertainty in corner frequency increases as the corner frequency approaches the signal bandwidth, which causes the confidence interval for each estimate to be asymmetric about the estimated value.

One of our most important improvements was to generalize the stacking approach that Shearer et al. (2006) used to obtain the EGF, while relaxing the assumption of self-similar scaling between the stacked spectra. Rather than assume a constant stress drop $\Delta\sigma$ for each moment-binned stack, we allow for the possibility of a variation in mean stress drop with moment, i.e., $\log_{10} \Delta\sigma = \epsilon_0 + \epsilon_1 \Omega_0$, where Ω_0 is relative moment. For five regions of dense seismicity in southern California (see Figure 1), we find that we can obtain a better fit if stress drop is permitted to increase with moment (see Figure 2).

However, this result depends upon an assumed high-frequency fall-off rate of 2, i.e., the Brune model. The fundamental observation is that the larger events have on average more high-frequency energy than predicted by a self-similar Brune model. This can be explained by breaking self-similarity such that the larger earthquakes have higher average stress drops than the smaller events. Alternatively, it can be explained by lessening the high-frequency falloff rate, which boosts the high-frequency energy observed for the larger earthquakes while not affecting the fit to the smaller earthquakes for which the corner frequency is near the upper limit of the data bandwidth. This creates a tradeoff between the degree of stress-drop scaling and the high-frequency falloff rate, which is illustrated in Figure 3 for the Yuha Desert study region, but which is found for the other study regions as well.

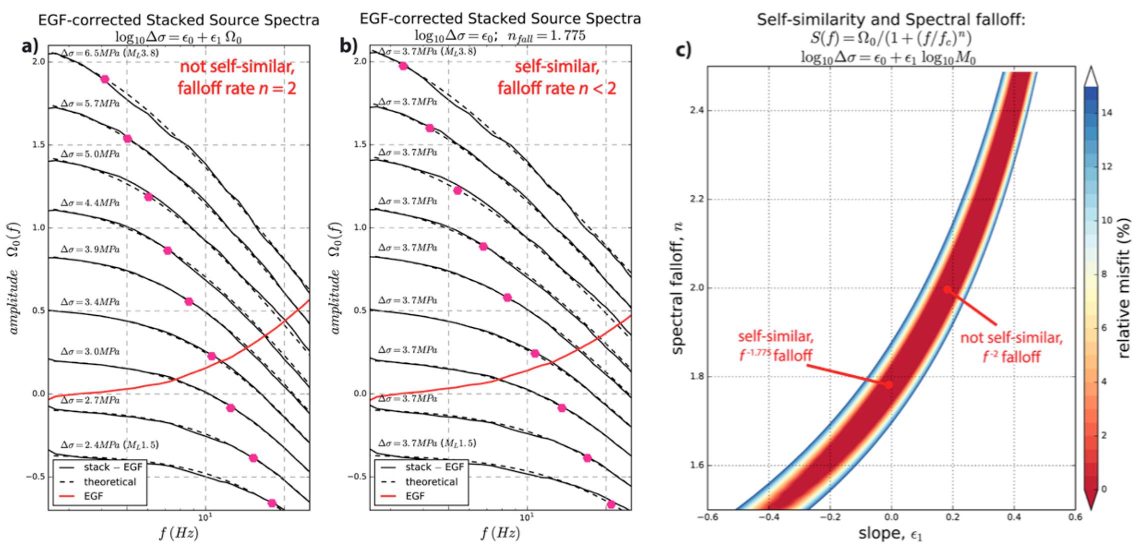

Figure 3. Example showing the tradeoff between stress-drop scaling parameter ϵ_1 and spectral falloff rate n, for stacked source spectra from the Yuha Desert region. (a) EGF-corrected, stacked source spectra (solid black lines, binned by spectral moment Ω_0) assuming a source model with ω^{-2} spectral falloff rate (n = 2) and scaling parameter $\epsilon_1 > 0$. In this model, $\log_{10} \Delta\sigma$ is permitted to vary linearly with $\log_{10} M_0$. (b) EGF-corrected source spectra (solid black lines, binned by spectral moment Ω_0), now assuming a source model with lower spectral falloff rate ($n < 2$) and fixed scaling parameter $\epsilon_1 = 0$. In this model, $\Delta\sigma$ is constrained to be invariant with M_0. (c) Contour plot of the relative misfit between the observed (EGF-corrected) and theoretical stacked spectra, plotted as a function of scaling parameter (ϵ_1, x axis) and high-frequency falloff rate (n, y axis). Source models that assume $n = 2$ (an ω^{-2} model) require $\epsilon_1 > 0$, while source models that assume $\epsilon_1 = 0$ (a self-similar model) require $n < 2$.

Coda wave analyses

Body-wave arrivals seen in local and regional earthquake records are followed by a wavetrain of scattered energy termed the coda, which is typically modeled using scattering theories for random media. A number of classic studies have analyzed local earthquake coda, including Aki and Chouet (1975), Sato (1977), Wu (1985), Frankel and Wennerberg (1987), Fehler et al. (1992), and many others (see review by Sato and Fehler, 1998). Most of these studies have focused on understanding coda behavior in terms of models of crustal and upper-mantle scattering strength and intrinsic attenuation. However, it is also possible to use coda waves to examine the spectral properties of the earthquake source, i.e., to resolve source spectra and estimate stress drop and radiated energy (e.g., Mayeda and Walter, 1996; Baltay et al., 2011; Abercrombie, 2013). Coda-wave approaches to source spectral measurements have the great advantage that they tend to average out radiation pattern and directivity differences in the spectra observed at individual stations (see Kaneko and Shearer, 2014, 2015, for a recent account of the importance of these effects).

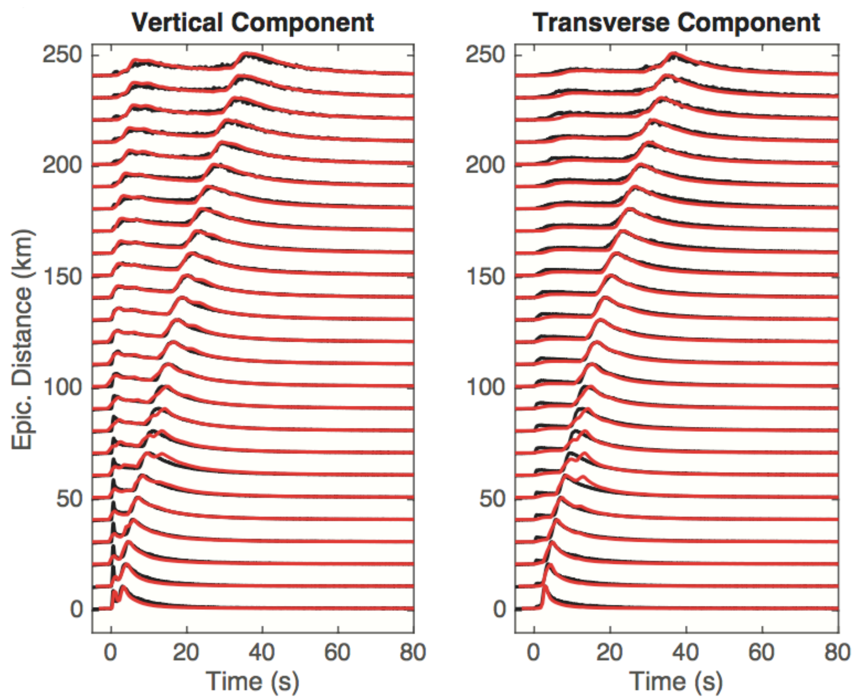

Figure 4. Vertical- and transverse-component envelope-function stacks are shown in black with model predictions from the Monte Carlo scattering code shown in red. The secondary S-wave peaks in the synthetics at 50 to 80 km range are Moho reflections from the 1D model, which are not seen clearly in the data stacks because of Moho depth variations across southern California.

We have begun a comprehensive study of coda behavior in southern California to examine both crustal structure and source properties. This is a new direction for my research program, although it is related to previous southern California work on attenuation structure (Hauksson and Shearer, 2006) and stress drop estimates from P-wave spectra (Shearer et al., 2006; Chen and Shearer, 2011; Goebel et al., 2015; Trugman and Shearer, 2017). Our approach has several stages: (1) stack coda envelopes from large numbers of earthquakes to obtain spatially averaged coda behavior as a function of distance, source depth, and frequency; (2) model these results using a multiple-scattering Monte Carlo seismic phonon algorithm (Shearer and Earle, 2004) to determine the best-fitting 1-D model of scattering properties and intrinsic attenuation; (3) compare these results to other methods, such as the multiple-lapse-time-window (MLTW) approach of Fehler et al. (1992); (4) analyze deviations of individual seismogram codas from the stacked average in order to characterize and model likely spatial variations in scattering strength and intrinsic attenuation; (5) apply methods similar to those developed by Mayeda and Walter (1996) and others to characterize source spectra for thousands of individual earthquakes.

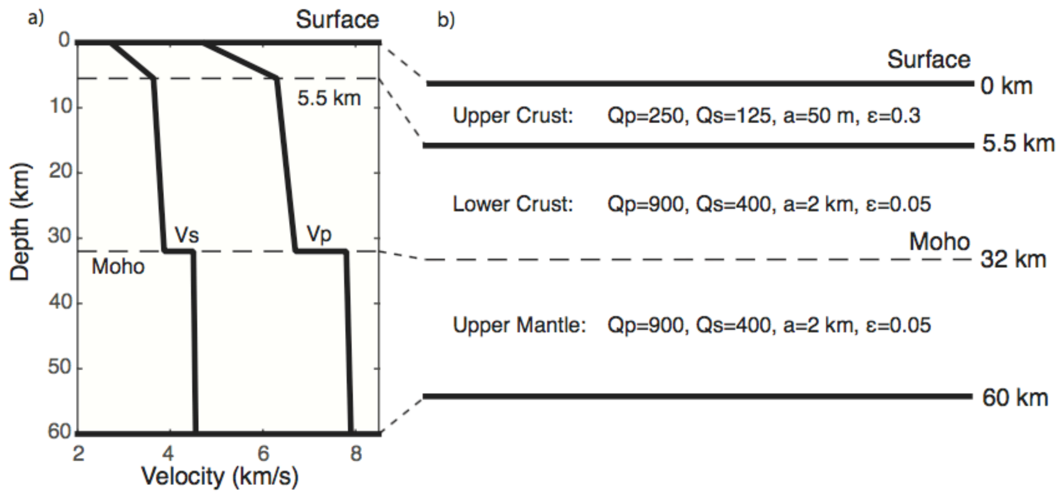

Figure 5. Our preferred 1D intrinsic and scattering attenuation model for southern California. The correlation distance *a* describes the scale of the velocity variations and ε gives their RMS fractional fluctuations.

We have largely completed stages (1) and (2) under current funding and have a paper in review describing the results (Wang and Shearer, 2017). We have applied a Monte Carlo method to track the random trajectories of millions of seismic energy particles that are sprayed from the source and then subject to scattering probabilities derived from random media theories (e.g., Gusev and Abubakirov, 1987; Hoshiba, 1991; Margerin et al., 2000; Shearer and Earle, 2004). The algorithm is fully elastic and includes both P- and S-wave single and multiple scattering. It computes scattering probabilities and scattering angles based on theoretical results for random heterogeneity models. The random medium is characterized by two parameters, the correlation distance, *a,* and the RMS fractional velocity fluctuation, ε. Figure 4 shows the coda stacks and the fit provided by our preferred model (Figure 5). The synthetic results generally fit quite well for both the P- and S- wave coda decay and the energy distribution between the direct and coda waves. We find that the range dependence in the data stacks can only be fit with models containing strong scattering and intrinsic attenuation in the shallow crust and weaker scattering and attenuation in the mid to lower crust. This result is important because many common approaches to analyzing coda waves assume simplified uniform half-space models and will produce misleading results when applied to more realistic depth-dependent models.

A great advantage of our approach is that we are able to obtain unified, energy-conserving models that can explain all of the main features that are seen in both direct waves and coda waves. The ultimate goal of this research is to understand, as a function of frequency, where the energy radiated from earthquakes is going, i.e., how much is contained in the direct wave arrivals, how much is scattered and where it goes, and how much is lost due to intrinsic attenuation. Although characterizing scattering properties and the power spectrum of crustal heterogeneity is very interesting from a theoretical point of view, this information is also fundamental for informing strong ground motion estimates at high frequencies, where scattering and attenuation effects are critical. Thus, it is important to characterize not only average crustal properties, but their aleatoric and epistemic variability, so that the variance in predicted ground motions can be quantified on local and regional length scales.

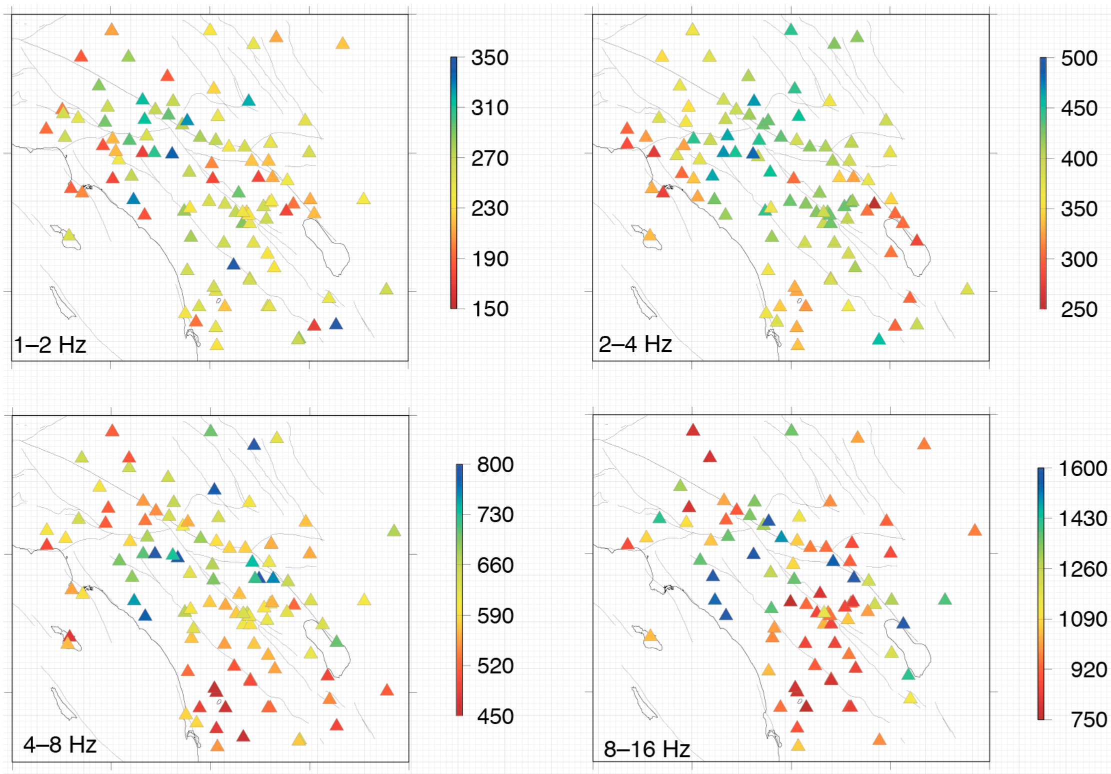

Figure 6. Observed coda Q variations in southern California as a function of frequency and station location. Coda Q increases with frequency, as shown by the different Q scales for each panel.

We have begun extending this work to explore lateral variations in coda strength and decay rate and their implications for scattering and intrinsic attenuation. Often lateral variability has been characterized by analyzing coda Q (a simple measure of the exponential decay of coda waves) as measured at different seismic stations and we will begin our study by performing a comprehensive coda Q analysis, decomposing the results into station, event, and path terms, and comparing our results to previous work. Figure 6 shows preliminary results for the station coda Q terms, which exhibit a strong frequency dependence. These results are generally consistent with previous work (Aki, 1996), but show some deviations at frequencies above 4 Hz. One advantage of our method is that we are able to explicitly test the hypothesis that near-station structure dominates coda Q variations (as compared to near-source or along-path structure) and we have been able to confirm this is the case for southern California. Eventually we plan to modify our Monte Carlo code to handle 3D variations in scattering strength in order to test what kinds of laterally varying models can explain the scale lengths of coda *Q* variations that are observed and what this implies for scattering and intrinsic *Q* variations.

References

Abercrombie, R. E., Earthquake scaling relationships from -1 to 5 ML using seismograms recorded at 2.5-km depth, *J. Geophys. Res.*, **100**, 24,915–24,936, 1995.

Abercrombie, R. E., Comparison of direct and coda wave stress drop measurements for the Wells, Nevada, earthquake sequence, *J. Geophys. Res.*, **118**, 1458–1470, doi: 10.1029/2012JB009638, 2013.

Abercrombie, R. E., S. Bannister, J. Ristau, and D. Doser, Variability of earthquake stress drop in a subduction setting, the Hikurangi Margin, New Zealand, *Geophys. J. Int.*, **208**, 306–320, doi: 10.1093/gji/ggw393, 2017.

Abercrombie, R. E., and J. R. Rice, Small earthquake scaling revisited: can it constrain slip weakening? *Geophys. J. Int.*, **162**, 406-424, 2005.

Aki, K., Scale dependence in earthquake phenomena and its relevance to earthquake prediction, *Proc. Nat. Acad. Sci.*, **93**, 3740-3747, 1996.

Aki, K., and B. Chouet, Origin of coda waves: source attenuation and scattering effects, *J. Geophys. Res.*, **80**, 3322-3342, 1975.

Baltay, A. S., and T. C. Hanks, Understanding the magnitude dependence of PGA and PGV in NGA-West 2 data, *Bull. Seism. Soc. Am.,* **104**, doi: 10.1785/0120130283, 2014.

Baltay, A. S., T. C. Hanks and N. A. Abrahamson, Uncertainty, variability, and earthquake physics in ground motion prediction equations, *Bull. Seism. Soc. Am.*, in review, 2017.

Baltay, A. S., T. C. Hanks and G. C. Beroza, Stable stress drop measurements and their variability: implications for ground-motion prediction, *Bull. Seism. Soc. Am.,* **103**, doi: 10.1785/0120120161. 2013.

Baltay, A., S. Ide, G. Prieto, and G. Beroza, Variability in earthquake stress drop and apparent stress, *Geophys. Res. Lett.*, doi: 10.1029/2011GL046698, 2011.

Brune, J., Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, **75**, 4997-5009, 1970.

Chen, X. and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, doi: 10.1029/2011JB008263, 2011.

Cotton, F., R. Archuleta and M. Causse, What is the sigma of the stress drop? *Seismol. Res. Letts.,* **84**, 42-48, doi: 10.1785/0220120087, 2013.

Fehler M., M. Hoshiba, H. Sato, and K. Obara, Separation of scattering and intrinsic attenuation for the Kanto-Tokai region, Japan, using measurements of S-wave energy versus hypocentral distance. *Geophys. J. Int.*, **198**, 787-800, 1992.

Frankel, A., and L. Wennerberg, Energy-flux model of seismic coda: separation of scattering and intrinsic attenuation, *Bull. Seismol. Soc. Am.*, **77**, 1223-1251, 1987.

Goebel, T. H. W., E. Hauksson, P. M. Shearer, and J. P. Ampuero, Stress drop heterogeneity within tectonically complex regions: A case study of San Gorgonio Pass, southern California, *Geophys. J. Int.*, **202**, 514–528, 2015.

Gusev, A. A., and I. R. Abubakirov, Monte-Carlo simulation of record envelope of a near earthquake, *Phys, Earth Planet. Int.*, **49**, 30-36, 1987.

Hauksson, E., Average Stress Drops of Southern California Earthquakes in the Context of Crustal Geophysics: Implications for Fault Zone Healing, *Pure Appl. Geophys.*, 1–12, doi:10.1007/s00024-014-0934-4, 2014.

Hauksson, E., W. Yang and P. M. Shearer, Waveform relocated earthquake catalog for southern California (1981 to June 2011), *Bull. Seismol. Soc. Am.*, **102**, 2239–2244, doi: 10.1785/0120120010, 2012.

Hoshiba, M., Simulation of multiple-scattered coda wave excitation based on the energy conservation law, *Phys. Earth Planet. Int.*, **67**, 123-136, 1991.

Kanamori, H. and E. E. Brodsky, The physics of earthquakes, *Reports on Progress in Physics*, **67**, 1429 - 1496, DOI:10.1088/0034-4885/67/8/R03, 2004.

Kaneko, Y., and P. M. Shearer, Seismic source spectra and estimated stress drop from cohesive-zone models of circular subshear rupture, *Geophys. J. Int.*, **197**, 1002–1015, doi: 10.1093/gji/ggu030, 2014.

Kaneko, Y., and P. M. Shearer, Variability of seismic source spectra, estimated stress drop and radiated energy, derived from cohesive-zone models of symmetrical and asymmetrical circular and elliptical ruptures, *J. Geophys. Res.*, **120**, doi: 10.1002/2014JB011642, 2015.

Kwiatek, G., Bulut, F., Bohnhoff, M., Dresen, G., High-resolution analysis of seismicity induced at Berlín geothermal field, El Salvador, *Geothermics*, **52**, 98-111, doi: org/10.1016/j.geothermics.2013.09.008, 2014.

Madariaga, R., Dynamics of an expanding circular fault, *Bull. Seism. Soc. Am.,* **66**, 639–666, 1976.

Malagnini, L., K. Mayeda, S. Nielsen, S.-H. Yoo, I. Munafo, C. Rawles, and E. Boschi, Scaling transition in earthquake sources: a possible link between seismic and laboratory measurements, *Pur. Appl. Geophys.*, **171**, doi: 10.1007/s00024-013-0749-8, 2013.

Margerin, L., M. Campillo, and B. V. Tiggelen, Monte Carlo simulation of multiple scattering of elastic waves, *J. Geophys. Res.*, **105**, 7873-7892, 2000.

Mayeda, K. and W.R. Walter, Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes, *J. Geophys. Res.*, **101**, 11,195-11,208, 1996.

Oth, A., D. Bindi, S. Parolai and D. Di Giacomo, Spectral analysis of K-NET and KiK-net data in Japan, Part II: On attenuation characteristics, source spectra, and site response of borehole and surface stations. *Bull. Seismol. Soc. Am.,* **101**, 667-687, doi: 10.1785/0120100135, 2011.

Prieto, G., R. Parker, and F. Vernon, A Fortran 90 library for multitaper spectrum analysis, *Computers and Geosciences*, **35**, 1701–1710, doi: 10.1016/j.cageo.2008.06.007, 2009.

Sato, H., Energy propagation including scattering effects, single isotropic scattering approximation. *J. Phys. Earth*, **25**, 27-41, 1977.

Sato, H., and M.C. Fehler, *Seismic Wave Propagation and Scattering in the Heterogeneous Earth*, Springer-Verlag, New York, 1998.

Shearer, P. M., G. A. Prieto, and E. Hauksson, Comprehensive analysis of earthquake source spectra in southern California, *J. Geophys. Res.*, **111**, B06303, doi:10.1029/2005JB003979, 2006.

Shearer, P.M. and P.S Earle, The global short-period wavefield modelled with a Monte Carlo seismic phonon method, *Geophys. J. Int.*, **158**, 1103-1117, 2004.

Trugman, D. T., and P. M. Shearer, Application of an improved spectral decomposition method to examine earthquake source scaling in southern California, *J. Geophys. Res.*, **122**, doi: 10.1002/2017JB013971, 2017.

Wang, W., and P. M. Shearer, Using direct and coda wave envelopes to resolve the scattering and intrinsic attenuation structure of southern California, *J. Geophys. Res.*, in review, 2017.

Wu, R.-S., Multiple scattering and energy transfer of seismic waves—separation of scattering effect from intrinsic attenuation—I. Theoretical modelling, Geophys. J. Roy. Astron. Soc., **82**, 57-80, 1985.

Zhang, Q., and P. M. Shearer, A new method to identify earthquake swarms applied to seismicity near the San Jacinto Fault, California, *Geophys. J. Int.*, **205**, doi: 10.1093/gji/ggw073, 2016.

Bibliography (Reports Published since 2012)

Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.

Chen, X., and P. M. Shearer, Analysis of foreshock sequences in California and implications for earthquake triggering, *Pure Appl. Geophys.*, doi: 10.1007/s00024-015-1103-0, 2015.

Chen, X., P. M. Shearer, and R. E. Abercrombie, Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi:10.1029/2011JB008973, 2012.

Goebel, T. H. W., E. Hauksson, P. M. Shearer, and J. P. Ampuero, Stress drop heterogeneity within tectonically complex regions: A case study of San Gorgonio Pass, southern California, *Geophys. J. Int.*, **202**, 514–528, 2015.

Hauksson, E., J Stock, R. Bilham, M. Boese, X. Chen, E. H. Fielding, J. Galetzka, K. W. Hudnut, K. Hutton, L. C. Jones, H. Kanamori, P. M. Shearer, J. Steidl, J. Treiman, S. Wei, and Wenzheng Yang, Report on the August 2012 Brawley earthquake swarm in Imperial Valley, Southern California, *Seismol. Res. Lett.*, **84**, 177-189, doi: 10.1785/0220120169, 2013.

Hauksson, E., W. Yang and P. M. Shearer, Waveform relocated earthquake catalog for southern California (1981 to June 2011), *Bull. Seismol. Soc. Am.*, **102**, 2239–2244, doi: 10.1785/0120120010, 2012.

Kane, D. L., P. M. Shearer, B. P. Goertz-Allmann, and F. L. Vernon, Rupture directivity of small earthquakes at Parkfield, *J. Geophys. Res.*, **118**, doi: 10.1029/2012JB009675, 2013.

Kaneko, Y., and P. M. Shearer, Seismic source spectra and estimated stress drop from cohesive-zone models of circular subshear rupture, *Geophys. J. Int.*, **197**, 1002–1015, doi: 10.1093/gji/ggu030, 2014.

Kaneko, Y., and P. M. Shearer, Variability of seismic source spectra, estimated stress drop and radiated energy, derived from cohesive-zone models of symmetrical and asymmetrical circular and elliptical ruptures, *J. Geophys. Res.*, **120**, doi: 10.1002/2014JB011642, 2015.

Shearer, P. M., Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.*, **117**, B06310, doi: 10.1029/2011JB008957, 2012a.

Shearer, P. M., Space-time clustering of seismicity in California and the distance dependence of earthquake triggering, *J. Geophys. Res.*, **117**, B10306, doi: 10.1029/2012JB009471, 2012b.

Sumiejski, P. E., and P. M. Shearer, Temporal stability of coda Q^{-1} in southern California, *Bull. Seismol. Soc. Am.*, **102**, 873–877, doi: 10.1785/0120110181, 2012.

Trugman, D. T., and P. M. Shearer, GrowClust: A hierarchical clustering algorithm for relative earthquake relocation, with application to the Spanish Springs and Sheldon, Nevada, earthquake sequences, *Seismol. Res. Lett.*, **88**, 1-13, doi: 10.1785/0220160188, 2017a.

Trugman, D. T., and P. M. Shearer, Application of an improved spectral decomposition method to examine earthquake source scaling in southern California, *J. Geophys. Res.*, **122**, doi: 10.1002/2017JB013971, 2017b.

Trugman, D.T., P. M. Shearer, A. A. Borsa, and Y. Fialko, A comparison of long-term changes in seismicity at the Geysers, Salton Sea, and Coso geothermal fields, *J. Geophys. Res.*, **121**, doi: 10.1002/2015JB012510, 2016.

Uchide, T., H. Yao, and P. M. Shearer, Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake, *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50144, 2013.

Wang, W., and P. M. Shearer, Using direct and coda wave envelopes to resolve the scattering and intrinsic attenuation structure of southern California, *J. Geophys. Res.*, in review, 2017.

Yang, W., E. Hauksson and P. M. Shearer, Computing a large refined catalog of focal mechanisms for southern California (1981–2010): Temporal stability of the style of faulting, *Bull. Seismol. Soc. Am.*, **102**, 1179–1194, doi: 10.1785/0120110311, 2012.

Zhang, Q., and P. M. Shearer, A new method to identify earthquake swarms applied to seismicity near the San Jacinto Fault, California, *Geophys. J. Int.*, **205**, doi: 10.1093/gji/ggw073, 2016.